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THE NATION'S LABORATORY FOR ADVANCED AUTOMOTIVE TECHNOLOGY

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MINUTEMAN III MOTOR-GENERATOR BEARING GREASE REPLACEMENT (FINAL REPORT)

July, 2013

by

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WINNER OF THE 1995 PRESIDENTIAL AWARD FOR QUALITY

U.S. Army Tank-Automotive Research,
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CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. BACKGROUND

The Minuteman III missile system has used Texaco Multifak AFB2 grease qualified under a military specification that has since been cancelled. Eventually, the Texaco product was used exclusively as a sole source product. This grease along with other lubricant business was acquired by another company (Chevron) and they abandoned this product line (2002-03 time frames). Based upon ChevronTexaco tests, their recommended substitute is not compatible with Texaco Multifak AFB2. To adopt the recommended substitute, the Air Force would have to remove all Motor-Generators (M-G) from storage and those installed in the sites to repack the bearings and return. This would involve over 500 assets that are operated 24/7 making it both strategically and financially not a feasible option. The M-Gs are lubricated yearly to extend operating life. The remaining grease supplies are past the recommended shelf life and degradation is unknown. To resolve this problem, Hill Air Force Base (AFB) is currently seeking new grease that provides same or better performance and must be compatible with the existing M-G grease. In addition, Hill AFB is looking to replace the current preservative oil (Capella WF-68 oil) for storing M-G bearings. As a part of the Hill AFB grease replacement project, TARDEC was asked to develop/find a new M-G grease and preservative oil for the Minuteman III Missile system.

2. GREASE TESTING PROGRAM

2.1. OBJECTIVE

The objective of this task is to develop/find a suitable lubricating grease (s) and preservative oil to replace Texaco Multifak AFB2 grease and Capella WF-68 oil, respectively.

2.2. SCOPE

This program evaluated a broad spectrum of lubricating greases used in military and industrial precision bearings as possible replacements of Multifak AFB2 grease, and performed a comprehensive series of laboratory tests in order to compare their properties. In this program, the grease compatibility was determined between candidate greases and Multifak AFB2 grease. As a result of this laboratory testing program, potential lubricating greases were identified for the Portsmouth Naval Shipyard (PNS) field tests. In this field test, the performance of the candidate greases was verified. Several new preservative oils were tested as replacements of Capella WF-68 oil. The duration of this study encompassed three years including laboratory testing and PNS field tests.

2.3 TEST PROTOCOL FOR GREASE COMPATIBILITY

The grease compatibility test was conducted according to ASTM D 6185 option II (10/90, 50/50, 90/10 ratio), Standard Practice for Evaluating Compatibility of Binary

Mixtures of Lubricating Greases. The first Stage tests consisted of the 100,000 cycle work stability, dropping point, and high temperature stability tests. If passed, the following test methods were used as the second Stage tests but only on the 50/50 mixture.

(1) Evaporation, ASTM E 1131
(2) Roll stability, ASTM D 1831
(3) Four ball wear test, ASTM D 2266
(4) Four ball EP test, ASTM D 2596
(5) Copper corrosion test, D4048
(6) Elastomer compatibility test, ASTM D 4289
(7) Distilled rust test, ASTM D 1743
(8) Salt water rust test, ASTM D5969 with 1% NaCl solution
(9) Oxidation stability test, ASTM D 5483
(10) Oil separation, ASTM D 6184

If the results obtained from all above tests were between those of the constituent greases, the mixture was compatible, while the failure of any test was noted as an incompatibility of the greases. The greases that pass these tests will continue to the full scale test protocol described next.

2.4. FULL SCALE TEST PROTOCOL FOR CANDIDATE GREASE

Candidate greases, which were compatible with Multifax AFB2 grease, were further evaluated according to the following full scale test protocol. Their physical and chemical properties were compared with Multifax AFB2 grease.

(1) Base oil viscosity (cSt) at 40 °C and 100°C (ASTM D 445)
(2) Water stability test (ASTM D7342 Procedure A)
(3) Channeling ability (FTM 791.7501)
(4) Low temperature stability test @ -40°C and -54 °C (FTM 791.7501).
(5) Dirt content (FTM 791.3005.4)
(6) Yield Stress point using Rheometer @ 25°C and 100 °C (ASTM draft procedure).
(7) Oil separation using Centrifuging test (Modified ASTM D 4425).
(8) Extreme Pressure property by SRV test (ASTM D 5706)
(9) Friction and Wear Property by SRV test (ASTM D 5707)
(10) Fretting wear test by SRV test (ASTM draft procedure)
(11) Biodegradation test by ASTM D 6731
(12) Laboratory 1000 hr Grease Life test by Modified ASTM D3527 method
(13) Storage stability @38 °C for 180 days (Consistency changes and Oxidation property changes), FTM 791.3467.1.
(14) Decomposition Kinetics, U.S. Army Method

2.5. GREASE SAMPLES FOR TEST

Candidate greases were selected based on the availability, performance, and potential compatibility with Multifak AFB2 grease. They consisted of military greases, commercial greases and new greases developed for this program. Table 1 lists the candidate greases for the grease testing program.

Table 1. Description of Candidate Greases

Grease	Base Oil Type	Thickener	Application	Stated Operational ranges
Multifak AFB2 (MFK)	Mineral	Lithium soap	M-G and Automotive	-40 to 170 °C
MIL-PRF-10924H (GAA-H)	PAO +Polyol ester	Lithium complex	Automotive multipurpose	-54 to 180 °C
MIL-PRF-81322G (WTR)	PAO	Clay	Aviation General	-54 to 180 °C
MIL-PRF-32014A (Two QPL Products , Nye, Castrol)	PAO	Lithium soap or clay	High speed in Air craft and Missile	-40 to 175 °C
MIL-PRF-10924G (GAA-G)	PAO +mineral	Lithium complex	Automotive Multipurpose	-54 to 180 °C
MIL-PRF-23827, Type 1 (Aeroshell 33) (GIA)	diester	Lithium soap	Instrument Bearing	-40 to 175 °C
Shell Alvania Grease RL2 (Shell)	PAO	Lithium soap	Electric motor bearing	-30 to 130 °C
LS1124	PAO	Lithium Soap	Multifak off-set	-40 to 170 °C
LS1124B	Mineral	Lithium Soap	Multifak off-set	-40 to 170 °C

2.6. TEST PROTOCOL FOR PRESERVE OIL

The Capella oil is currently used as preservative oil for M-G bearings. Due to the replacement of Multifak AFB2 grease, it was necessary to re-evaluate Capella WF-68 oil with candidate greases and find a replacement of Capella WF-68 oil if needed. The following test protocol was used to evaluate Capella WF-68 oil and candidate preservative oils. The Capella WF-68 oil served as a baseline oil in this evaluation.

(1) Kinematic Viscosity @40, -40, -54 °C (ASTM D 445)
(2) Flash ad fire points (ASTM D 92)
(3) Pour point (ASTM D 97)
(4) Precipitation Number (ASTM D 91)

(5) Evaporation Loss (ASTM D972 or ASTM E 1131)
(6) Acid and Base Number (ASTM D 974)
(7) Rust Protection in Humidity Cabinet (ASTM D 1748)
(8) Copper corrosion test (ASTM D 130)
(9) Bimetallic corrosion test (ASTM D6547)
(10) Low temperature stability test (FTM 791. 3458 @-45 C)
(11) Oxidation test (ASTM D 6186)
(12) Four ball wear test (ASTM D 4172)
(13) Water content (ASTM D 6304)
(14) Storage stability test with bearings at 25 C for 180 days
(15) Compatibility test between candidate grease and oil (Modified ASTM D 1743)
(16) Friction, wear and EP test using SRV test machine (ASTM D6425)

2.7. OIL SAMPLES FOR TEST

- Capella WF-68 oil (Supplied by Hill AFB)
- MIL-PRF-32033
- MIL-PRF-6085
- MIL-PRF-7870
- MIL-DTL-53131

2.8. 1000 hr PNS TEST

The PNS field test was conducted to verify the performances of candidate greases using actual M-G-equipment. This test was scheduled as the final Phase of this program. The following tasks were identified for the PNS testing plan.

(1) Develop field test plan (Harris Consulting International Company).
(2) Provide candidate greases for PNS test (TARDEC).
(3) Inspect and analyze test bearings before and after PNS test (TIMKEN).
(4) Conduct the 1000 hr field test using M-G equipment (PNS).
(5) Inspect and analyze candidate greases after PNS test (TARDEC).
(6) Monitor overall PNS test (TARDEC).

2.9. DELIVERY

- Candidate greases for PNS test
- Interim report for laboratory test
- Final report with recommendations

2.10. POINT OF CONTACT

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2.11. Milestones

Table 2. Milestones of Grease Replacement Program

Task	FY 10		FY 11				FY 12			
	3Q	4Q	1Q	2Q	3Q	4Q	1Q	2Q	3Q	4Q
Complete test plan and preliminary coordination (Kick off Meeting)	XX									
Conduct market study for military/non-military greases	XX	X								
Procurement of test samples	X	XX								
Procurement of SRV Tribology test machine	XX	XXX								
Conduct baseline test with Multifak AFB2 grease		XXX								
Conduct baseline test with Capella oil		XXX								
Initiate contract to Harris consulting	X	XXX								
Initiate contract to TIMKEN for bearing inspection	X	XXX								
Conduct grease compatibility test	X	XXX	XX							
Full scale laboratory tests for candidate greases			XX	XXX	XXX					
Full scale laboratory tests for preservative oils			XX	XXX	XXX	XXX				
Review and prepare interim report						X	XXX			
Coordinate contractors, PNS, and Hill for PNS test						XXX				
Monitor PNS full scale test and work on problem							XXX	XXX		
Coordination used bearing inspection and evaluate PNS used greases									XXX	
Review and final report									X	XXX

3. LABORATORY TEST RESULTS

3.1. Compatibility test

Compatibility is an important characteristic for a mixture of two greases. One of the issues always raised is the compatibility of existing grease versus new grease, especially during a changeover or addition of greases. Several compatibility test procedures are currently available to determine grease compatibility. Some military grease specifications also require a grease compatibility test in their qualification tests. This test procedure tends to determine the chemical reaction between greases by the physical and chemical property changes (i.e., high oil separation, grease consistency change, or oxidation) at elevated temperatures. However, this procedure does not provide a comprehensive compatibility between greases and other materials such as metals or elastomers deemed necessary for grease products. The lubricating greases are usually formulated with different types of base oil or a mixture of base oils, different types of thickeners, and different types of additives to meet the performance requirements of respective applications. Generally, when greases are incompatible with one another, the mixture may be inferior in service performance to either component product. It may show up in thermal-oxidation stability, consistency stability, or mechanical stability. This result could lead to premature lubricant, bearing and component failures. To minimize the incompatibility between two greases, most grease companies recommend that the existing residual grease be removed and cleaned from bearings or parts before it is packed with another type of grease. But, the removal of the existing grease is almost impossible in some grease applications such as the M-G system which are continuously operated without any interruption for many years. On the other hand, if greases are physically and chemically compatible with one another, changeover or adding grease is not considered an issue.

For this reason, Hill Air Force Base requested TARDEC to determine whether candidate greases are compatible with Mutifak AFB2 grease which is currently lubricating the M-G bearings. Practically, the compatibility is usually determined in service or by means of simulated functional tests. However, this approach is often difficult to use due to their wide range of operating conditions, the large number of possible materials in the systems, and the long testing time. Because of this, the grease compatibility testing program was divided into two Phases. The first Phase covered the laboratory compatibility test for the candidate greases with Multifak AFB2 grease, and the second phase was designed to verify the result obtained from the first phase at the field test which will be performed using the actual M-G unit. Therefore, the approach used in the laboratory compatibility test was to comprehensively evaluate the physical and chemical properties of a mixture of two greases according to the ASTM D 6185 Option II and U.S. Army Test Protocol for the second stage evaluation.

To perform the laboratory compatibility test, the test samples were homogeneous mixtures of two greases in three blending ratios by weight percent: 10:90, 50:50, 90:10. These blending ratios cover the range of blending which can occur in the field when they add grease in a system. A 50:50 mixture simulates a ratio that might be experienced

ideally when new grease is evenly distributed in a bearing containing existing grease. The 10:90 and 90:10 ratios are intended to simulate what might occur when different grease is added to an already lubricated bearing. The evaluation criteria used in this compatibility test is in the ASTM D 6185 test method which is shown in Table 3.

Table 3.Compatibility Rating System

Compatibility Rating	Evaluation Criteria
Compatible	Compatibility data are within data obtained from original two products
Borderline Compatible	Compatibility data are not within data obtained from original two products. But their difference is within the test precision.
Incompatible	Does not meet the above criteria.

The first stage of compatibility test consists of three essential tests identified earlier in the report. These tests are very widely used to predict the compatibility of greases under a laboratory environment. The evaluation criteria used in this testing program was that test results must be between or better than those of the individual greases. Table 4 summarizes the test results obtained from the first stage tests using eight candidate greases. The table shows that all greases, except for MIL-PRF-81322G (WTR) grease, passed the first Stage compatibility tests. WTR grease was rated as a borderline. Generally, clay based greases (e.g., WTR) are not compatible with lithium based greases (e.g., Multifak AFB2) due to typically incompatible thickening systems.   For this reason, the WTR grease is no longer considered a replacement for Multifak AFB2 grease.

All candidate greases, except for MIL-PRF-81322 grease, were moved to the next stage of compatibility test. The second stage compatibility test was designed using the ASTM standard tests related with material compatibility. These tests have been used to detect the grease-metal compatibility or the unwanted chemical reaction by their additives.   The test protocol consists of evaporation, roll stability by shear action, wear and EP tribology properties using ball bearings, copper corrosion test, rust test, elastomer compatibility test, oil separation, and oxidation stability test.   For the second stage tests, the 50:50 grease mixture is used because the other ratios (i.e., 90:10 or 10:90) do not significantly affect the grease compatibility. The evaluation criteria are the same as those of the first stage test used. Table 5 summarizes the test results by “Pass or Failure”. All greases tested in this second stage were passed.

Incompatibility of greases is usually evident in their consistency stability, mechanical stability, material compatibility, and thermal-oxidation stability. If greases are incompatible with one another, their mixtures may undergo softening in penetration (hardness) due to grease structure changes or a significant decrease in grease life expectancy. In these tests, consistency and mechanical stability of greases are determined by 100,000 work stability test and roll stability test. Both tests were designed to measure the penetration changes in consistency due to the continuous application of shearing

forces. In these tests, if the mixtures have a mechanical stability problem, they usually appear normal before being subjected to service but will soften rapidly ("turn to soup") upon working due to the incompatibility of their thickener systems. The test results indicated that the mixtures did not show any abnormal behavior and met the compatibility criteria.

The thermal-oxidation stability of the mixture of candidate greases with Multifak AFB2 grease was comprehensively evaluated using the results obtained from dropping point test, oil separation, evaporation, and oxidation stability. The test results showed that none of the candidate greases failed any of these tests. No adverse chemical reaction was observed in these tests indicating the additive package used in each candidate grease is compatible with those in Multifak AFB2 grease. These results indicated that the candidate greases are compatible with Multifak AFB2 grease in high temperature performance.

Metal and Elastomer compatibility tests are included to further evaluate additive/grease compatibility between greases, as an adverse change in performance is an indication of incompatibility. The grease compatibility with metals can be measured by a number of tests including copper corrosion test and rust test. These techniques usually involve exposing the metal to the mixture under a variety of conditions and determining any changes in the grease or the metals. The chemical stability of the mixture is also detected in these tests. The test results clearly indicated that all candidate greases were compatible with Multifak AFB2 grease.

Therefore, all candidate greases, except for MIL-PRF-81322 grease, passed all selected compatibility tests and did not show any sign of incompatibility with Multifak AFB2 grease under the laboratory environments.

Table 4. Test Results of Grease Compatibility (1st Stage)*

Grease	**100,000 Strokes (Penetration #)**					**Thermal Stability @ 120°C for 70 Hrs (Penetration #)**					**Dropping Point (°C)**					**Results**
MFK	**100**	**90:10**	**50:50**	**10:90**	**0**	**100**	**90:10**	**50:50**	**10:90**	**0**	**100**	**90:10**	**50:50**	**10:90**	**0**	
MFK:WTR	311.0	310.0	310.0	306.0	329.0	238.0	268.0	284.0	318.0	305.0	203.0	199.0	212.0	316.0	316.0	**Fail**
MFK: NYE	311.0	314.0	312.0	331.0	357.0	238.0	249.0	255.0	303.0	317.0	203.0	206.0	211.0	215.0	217.0	Pass
MFK:CASTR	311.0	315.0	321.0	322.0	322.0	255.0	256.0	276.0	307.0	310.0	203.0	210.0	212.0	228.0	234.0	Pass
MFK:GAA-H	311.0	307.0	306.0	309.0	305.0	252.0	259.0	283.0	296.0	297.0	203.0	205.0	210.0	316.0	316.0	Pass
MFK:SHELL	311.0	312.0	332.0	340.0	350.0	256.0	256.0	258.0	275.0	287.0	203.0	202.0	194.0	184.0	184.0	Pass
MFK:GIA	311.0	327.0	320.0	327.0	332.0	255.0	257.0	261.0	262.0	263.0	203.0	202.0	197.0	193.0	189.0	Pass
MFK:LS1124	311.0	307.0	296.0	301.0	290.0	255.0	255.0	256.0	256.0	257.0	203.0	203.0	200.0	197.0	196.0	Pass
MFK:LS1124B	311.0	298.0	289.0	279.0	279.0	261.0	258.0	256.0	260.0	261.0	203.0	203.0	201.0	196.0	193.0	Pass
MFK[1]:GAA-G	327.0	323.0	327.0	325.0	321.0	258.0	258.0	290.0	310.0	311.0	201.0	203.0	270.0	292.0	307.0	**Pass**

**Compatibility of blends must be between those of individual grease*

1. Different production batch was used in this mixture

Table 5. Test Results of Grease Compatibility (2nd Stage) 50:50 Mixture

TEST	MFK-NYE	MFK-CASTR	MFK-GAA-H	MFK GAA-G	MFK-SHELL	MFK-GIA	MFK-LS1124	MFK-LS112B
Evaporation, ASTM E1131	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Roll Stability, ASTM D1831	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Four Ball Wear, ASTM D2266	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Four Ball EP. ASTM D 2596	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Copper Corrosion, ASTM D 4048	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Distilled Rust test, ASTM D1743	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Saltwater Rust test, ASTM D 5969, 1 % NaCl	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Oxidation Stability Test, ASTM D 5483	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Oil Separation, ASTM D6184	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Elastomer Compatibility, ASTM D 4289	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass

3.2 Evaluation of Grease Performance

Operational performance is also a very important criterion for selecting replacement grease. The test protocol was developed using the ASTM F 2489, Precision Bearing Grease Guide. All candidate greases (except for MIL-PRF-10924G grease) that passed compatibility criteria were evaluated. The MIL-PRF-10924G grease has been superseded by MIL-PRF-10924H grease and is no longer available in the military system. In this evaluation, the Multifak AFB2 grease was tested to establish the baseline performance. This grease has successfully lubricated M-G bearings, which are spherical roller precisions bearing, for many decades. So far, there has been no negative lubrication performance observed in the M-G system, except it is unavailable. For this reason, the candidate greases must provide similar or better lubrication performance than Multifak AFB2 grease. Table 6 provides the test protocol and summarizes test results obtained from the candidate greases and Multifak AFB2 grease.

The most distinguishing property of a grease is its consistency which is related to the hardness or softness of the grease. The consistency is rated by the penetration number. It is defined as the depth, in tenths of a millimeter, that a standard cone penetrates a sample

of grease under prescribed conditions of weight, time and temperature. To ensure a uniform sample, a grease is worked 60 strokes using a grease worker before running the penetration test. The results are classified by grade ranging from 000 (very soft) to 6 (very hard) using the National Lubricating Grease Institute (NLGI) grease classification system. The test results showed that candidate samples rated as between NLGI No.1 and 2 grades. Multifak AFB2 grease was rated as a NLGI No.2 grade. Typically, NLGI No. 2 grade grease has been used in most bearing applications because of its medium consistency.

The mechanical (shear) stability of greases is usually evaluated by the work and water stability tests, and roll stability test. In these tests, the stability of greases is determined based on the measurement of penetration changes in consistency due to the continuous application of shearing forces with and without water present. If a grease has a mechanical stability problem it will usually appear normal before being subjected to service, but will soften rapidly or harden upon working. This can lead to a lubrication failure in mechanical components, such as bearings. In these tests, three candidate greases (i.e., GIA, Nye, and Castrol) had substantial problems with water stability, while the other candidate greases did not show any abnormal behavior as compared to the Multifak AFB2 grease. It appeared that GIA grease has a high degree of instability in the wet condition.

The thermal stability of the lubricating greases was evaluated using the results obtained from the dropping point and evaporation tests. The dropping point measures the high temperature operability and is dependent on the type of thickener used in grease. A high dropping point grease usually provides better thermal stability to ensure good bearing life at high temperatures. MIL-PRF-10924H grease had the highest dropping point value among them, while the other candidate greases showed a medium dropping point comparable to Multifak AFB2 grease. Due to the chemical structure of the thickening system, the lithium-complex thickener provides higher temperature resistance than that of the standard lithium thickener. However, high temperature resistance may not be significant for the operation of M-G system due to its low operation temperature (i.e., 43 °C). The evaporation loss at elevated temperatures also indicates the degree of the thermal stability of greases. All candidate greases were considered acceptable when compared to the Multifak AFB2 grease baseline.

Oxidation stability is another important property of candidate greases and is intended to predict their storage and service life. To evaluate oxidative life of lubricating greases, oxidation tests were conducted using the ASTM D5483, Pressure Differential Scanning Calorimeter (PDSC) method. This test method measures the differential heat flow between a sample and a reference thermocouple at various temperatures (155 C, 180 C, and 210 C) under a pressure of 3.5 MPa. In this procedure, the degree of oxidation stability at a given temperature is determined by measurement of induction time. The PDSC test results showed that Multifak AFB2 grease had very poor oxidation stability, while all candidate greases ranged from good to excellent. It is anticipated that none of the candidate greases will have any oxidation stability problem in the M-G-system.

Tribology (friction, wear, lubrication) properties are important operational parameters in conventional mechanical systems. Most lubricating greases often use anti-wear and EP additives to improve their wear prevention properties. This property is usually evaluated by the Four Ball Wear and Extreme Pressure (EP) Tests. In the Four Ball EP test, the Multifak AFB2 grease had a very low welding point (i.e., 100 kg) when compared to the candidate greases. This result was also confirmed in the SRV test which measures wear/EP property under oscillation conditions. The load carrying capacity property of Multifak AFB2 grease was much poorer than the other greases tested. Beside this property, all tested greases had very similar tribology properties including the friction coefficient of grease. The fretting wear is often found when the bearing is operated under load and in the presence of repeated relative surface motion causing vibration. This property is currently measured using the ASTM D 7594, SRV fretting wear test method. The test results indicated that no candidate greases will create a fretting wear problem in M-G bearings based on the fretting wear property of Multifak AFB2 grease.

Excessive oil separation often indicates grease degradation during service or storage periods. To assess this physical property, a static oil separation test was conducted using the ASTM D6184 test method. The results did not indicate any abnormal oil separation from the tested greases including Multifak AFB2 grease. To verify this result, dynamic oil separation tests were conducted using the modified ASTM D4534 Method, Oil Separation from Lubricating Grease by Centrifuging (Koppers Method). The results indicate that three candidate greases (i.e., Castrol for MIL-PRF-32014A, Shell Alvania RL-2, and GIA) experienced severe oil separation greater than Multifak AFB2 grease. It implied that these candidate greases are physically not stable under centrifugal force and it is anticipated that such a grease could have reduced lubrication life under bearing operation. The other candidate greases provided the same quality of performance observed with the Multifak AFB2 grease.

Corrosion prevention and good water stability are also important properties to prevent rust on bearing surfaces and to preserve grease consistency. In the corrosion protection property, the Multifak AFB2 grease showed very poor rust protection on the tested bearings under both fresh and saltwater environments. Of the candidate greases, only MIL-PRF-10924H grease passed both the fresh water and saltwater rust tests. All other candidate greases passed the fresh (distilled) water rust test but failed the saltwater rust test. The MIL-PRF-10924H grease was originally formulated to pass the saltwater rust protection and has been used extensively in military tactical and combat ground equipment. In the water stability test, it was observed that GIA grease had a very severe problem with water. The copper corrosion test is one test designed explicitly to detect corrosion on copper metal/alloys which is known as a very corrosion sensitive metal. No candidate grease exhibited any corrosion problems with cooper metal nor did Multifak AFB2 grease.

The low temperature property of grease is one of the important operational parameters for mechanical systems. If grease becomes too hard under sub zero temperatures, mechanical systems such as bearings, can lose lubrication and require higher torque. This

can result in fatigue failure of mechanical systems. Currently, this property is measured using a mechanical torque tester that simulates an automobile wheel bearing system. For the evaluation, three grease samples were tested at – 54 °C, using the FED-STD-791D, Low Temperature Grease Torque test procedure. The results confirmed that four candidate greases (i.e., MIL-PRF-10924H, MIL-PRF-32014A, MIL-PRF-23827, and LS1124) were designed for extreme low temperature, -54 °C, while three commercial greases including the Multifak AFB2 grease were formulated to use at -40 °C and failed. It should be noted the passing greases were formulated using synthetic oil.

Biodegradation is a natural process caused by the action of microorganisms in the presence of oxygen, nitrogen, phosphorous, and trace minerals. Organic pollutants can support microbial growth and are converted into a series of oxidation products that ultimately conclude with carbon dioxide and water. Generally, biodegradability is the ability of a product to naturally degrade when exposed to the environment, i.e., soil or water. Products that are biodegradable are considered less toxic and more environmentally friendly. Currently, this technology has been mandated in order to reduce the generation of hazardous wastes by petroleum based or synthetic oils which result in both short and long term liabilities in terms of costs, environment damage, and mission performance. For this reason, the biodegradability of grease is considered an important property, environmentally speaking, for selecting the grease for the M-G system. To assess this property, the candidate greases and Multifak AFB2 grease were tested using both ASTM D 6731 and ASTM D7373 biodegradation test methods. The test results indicated that Multifak AFB2 grease is classified as a non-biodegradable grease, while MIL-PRF-10924H and GIA greases are readily biodegradable greases. A product is considered readily biodegradable when it degrades at a rate greater than or equal to 60% within a 28 day test period. Currently, the military supports the use of environmentally acceptable products in military systems as long as mission and performance requirements are met.

Elastomer seals that fail to retain and or exclude contaminants when exposed to grease are considered incompatible. The deterioration of elastomer seals results in oil leakage as oils are released from the grease. The best method of determining whether a grease and an elastomer are compatible is to observe them in actual systems. Unfortunately, this approach is almost impossible due to limited availability of equipment and high cost. For this reason, many grease users often require an elastomer compatibility test using an actual equipment elastomer. Currently, the M-G unit uses O-rings to seal the housing and prevent grease migration. For the last 20 years, there has been no seal failure in M-G units. This indicates that Multifak AFB2 grease is compatible with the seals used in the M-G system. To determine the compatibility between the O-ring and candidate greases, all grease samples were evaluated using the ASTM D4289, laboratory elastomer compatibility test method. In this test, the hardness change of the elastomer was determined using a piece of the elastomer sheet due to the limited surface of an O-ring. This elastomer sheet was made of Acrylonitrile-Butadiene (NBR) and is the same material used in the O-ring. Table 6 reports the results of elastomor compatibility testing for candidate greases and Multifak AFB2 grease. All tested greases except for GIA were compatible with the elastomer material used in the M-G system. GIA exposure to the

elastomer material resulted in a very severe swelling as shown in Figure 2. This severe swelling clearly demonstrated GIA is incompatible with the elastomer in the M-G system. This grease is not acceptable for use in the M-G system.

Table 6. Physical and Chemical Properties of Candidate Greases

Test	Test Method	MFK (Air Force M-G grease)	GAA-H, MIL-PRF-10924H	Nye, MIL-PRF-32014A, QPL 1	Castrol, MIL-PRF-32014A, QPL 2	Shell Alvania RL-2	GIA, MIL-PRF-23827 Type I	LS1124, Experimental grease A	LS1124B, Experimental grease B
Dropping Point I	D 2265	203	>316	217	234	184	189	196	193
Worked Penetration	D 217 NLGI	270 No.2	270 No. 2	323 No.1	290 No. 2	303 No.1.5	295 No. 2	286 No.2	268 No.2
Oxidation Stability (PDSC), @180C, min	D 5483	17.7	143	160	193	186	343	257	160
Water Stability, Procedure B, ΔP	D7342	45	28	74	73	36	129	16	-6.0
Evaporation Loss (TGA), %,100C, 1 hr	E 1131	0.29	1.0	0.23	0.18	0.9	0.54	0.12	0.28
Oil separation, %	D6184	3.55	0/1	6.9	6.4	8.2	3.7	2.5	4.3
Four ball wear, mm	D 2266	0.67	0.44	0.39	0.34	0.45	0.69	0.46	0.46
Four ball EP	D 2596	W:100 kg LWI:23.1	W:250 LWI:38.0	W:200 LWI:42.1	W:200 LWI:35.8	W:160 LWI:33	W:315 LWI:43	W:200 LWI:36.6	W:200 LWI:36.3
Worked Stability	D217	41	27	34	32	47	27	4	11
Saltwater corrosion, 1 % NaCl	D5969	Fail	Pass	Fail	Fail	Fail	Fail	Fail	Fail
Distilled water corrosion	D1743	Fail	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Roll stability	D 1831	31	0	18	12	14	10	10	-17
Copper corrosion	D4048	1b	1b	1b	1b	1b	1b	1b	1b
Oil separation by centrifuging, %, 2hrs	U.S. Army	12.53	6.9	18.72	26.65	23.72	35.27	13.19	7.63
Elast. Compatibility Swelling change %, hardness change, %	D4289	5.9 -3	23.0 -8	19.9 -3	18.4 -3	6.5 -3	83.6 -14	3.9 -4	11.0 -6
Base oil viscosity @40°C, cSt	D445	48	30.3	121	131.7	98	11.8	46.8	47.7
Base oil viscosity, @100°C, cSt	D445	7.3	6.2	16.9	17.7	9.4	7.5	7.9	7.6
Dynamic viscosity @40°C, 25s-1, pa.s	ASTM draft Rheology procedure	20.2	32.4	27.6	17.0	37.4	33.8	18.4	22.0
Biodegradation (1), %	D7373	34.1	65.4	42.3	42.4	33.7	78.9	41.6	34.7

Test	Test Method	MFK (Air Force M-G grease)	GAA-H, MIL-PRF-10924H	Nye, MIL-PRF-32014A, QPL 1	Castrol, MIL-PRF-32014A, QPL 2	Shell Alvania RL-2	GIA, MIL-PRF-23827 Type I	LS1124, Experimental grease A	LS1124B, Experimental grease B
Biodegradation (2), %	D6731	41.9	60.0	27.9	28.5	32.8	77.7	36.4	40.0
Dirt content	FM-791.3005.4	875	600	275	175	476	50	250	275
Yield stress @25C, 100°C, pa.s	ASTM draft Rheology procedure	435.4	186.5	379.5	245.4	40.5	542.0	503.4	472.7
Fretting wear, SRV	D7594	0.57	0.59	0.35	0.39	0.38	0.75	0.53	0.52
Friction & wear, SRV	D5707	F: 0.12 W:0.77	F: 0.83 W:0.13	F: 0.11 W:0.44	F: 0.12 W:0.49	F: 0.11 W:0.45	F: 0.15 W:0.93	F: 0.12 W: 0.5	F: 0.13 W:0.51
EP , LWI, N, SRV	D5706	350	1400	2000	2000	1600	900	499	900
Low temperature torque, N.m, @-54°C	FED-STD-791D	Breakaway: 24 Running: 6.8	3.6 1.9 @-40°C	9.6 3.5	7.5 3.2	11.5 4.3 @-40°C	0.9 0.4	2.4 1.2	31.8 7.6

3.3 Laboratory Dynamic Test

The high temperature endurance life of grease is another important operational parameter for a mechanical system. This property usually defines the upper operational temperature in service. Currently, several functional test methods are available to measure the grease high temperature life. Among them, the ASTM D3527 Method, Life Performance Test of Lubricating Greases, is widely used in the grease industry and by users. This method evaluates all individual physical properties of greases directly related to high temperature and shear, using a simulated front wheel bearing system and a dynamic laboratory bench-type test apparatus which is shown in Figure 1. To verify the high temperature performances of candidate greases, all candidate greases including Multifak AFB2 grease and their 50% mixtures were tested using the modified ASTM D3527 test method. This modification was essentially needed to simulate the field operation parameters of an M-G unit for temperature and RPM. The laboratory dynamic tests were performed at 83 °C (180°F) and 1800 rpm for 1000 hrs without any interruption. These test parameters were adopted from the PNS grease qualification test which will be scheduled at Portsmouth Naval Shipyard (PNS).   During the test, torque level and noise level were monitored every day, and the grease samples were visually inspected and analyzed using a grease decomposition kinetic model after the tests. The test results showed that no greases failed. It was observed that candidate greases oxidized between 5.3 % and 27% and their predicted lives were calculated between 0.51 and 3.4 years in the taper roller bearing test. Table 7 summarizes the decomposition kinetic life of tested greases and their oxidation conditions based on the laboratory simulated M-G bearing test. The results of this dynamic test imply that the candidate greases and their mixtures will not have any problem in the PNS grease qualification test.

Table 7. High Temperature Grease Life using a Decomposition Kinetic Model

Sample	Induction time before 1000 hr test, @180°C, min*	Induction time after 1000 hr test, @180°C, min	Decomposition Kinetic Life @ 83 °C, hrs	% Grease oxidized for 1000 hr test	Predicted grease life in the taper roller bearing test @ 83 °C, yrs
MFK	9.07	4.0	5508	13	0.71
NYE	46.5	29.7	5058	5.3	2.2
Castrol	74.8	60.0	4104	22	0.52
Shell	72.6	30.6	1027	15	1.4
GIA	33.1	14.7	1510	13	1.34
GAA	31.8	17.6	1126	6.3	2.4
LS1124	78.6	35.6	6966	12.0	0.74
LS1124B	63.4	21.4	4671	21.0	0.51
NYE 50 %	78.1	35.3	6079	12.0	0.75
Castrol 50%	25.7	14.9	4073	7.0	1.8
Shell 50%	54.5	28.4	1766	9.2	2.2
GIA 50%	26.2	10.4	2334	16.0	0.84
GAA 50 %	29.2	8.2	1886	27.0	0.51
LS1124 50%	30.9	23.8	4388	2.3	3.4
LS1124B 50%	27.5	14.3	2197	9.0	1.9

* Pre-run @ 1800 rpm and 83°C for 3hours

3.4 Summary of Grease Evaluation

Table 8 briefly summarizes the evaluations on tested greases. This table describes their performances, compatibility with Multifak AFB2 grease, 1000 hr grease life test, and availability.

Table 8. Evaluation of Candidate Greases

Grease	Evaluation
Multifak AFB2 (MFK)	• M-G bearing grease • Availability problem • Poor corrosion protection • Poor oxidation stability • Not high temperature grease • Low load carrying capacity • Passed 1000 hr grease life test
MIL-PRF-10924H (GAA)	• Military Automobile grease • Compatible with MFK • Excellent corrosion protection grease • Wide operational temperatures (-54 to180 C) • Biodegradable grease • Widely available in the military system • Passed 1000 hr grease life test
MIL-PRF-81322 (WTR)	• Military aviation general purpose grease • Not compatible with MFK
MIL-PRF-32014 (NYE, CASTROL)	• Air Force instrument bearing grease

Grease	Evaluation
	• Compatible with MFK • Medium operational temperature grease (-54 to 150C) • Water stability problem • High oil separation problem • Available in the military system • Passed 1000 hr grease test
Shell Alvania RL-2 grease (Shell)	• Commercial electric motor grease • Compatible with MFK • Oil separation problem • Medium temperature grease (-40 to 120C) • Low temperature operational problem (-40C) • Passed 1000 hr grease life test • Not available in the military system
MIL-PRF-10924G (GAA-G)	• Military old automobile grease • Compatible with MFK • Excellent corrosion protection • Wide operational temperatures (-54 to180 C) • No longer available in the military system • Passed 1000 hr grease life test
MIL-PRF-23827 Type 1 (GIA)	• Military instrument & aviation grease • Compatible with MFK • Low temperature grease (-73 to 121 C) • Clean grease • Severe oil separation problem • Water stability problem • Incompatibility with O-ring used in M-G unit • Poor oxidation • Passed 1000 hr grease life test • Available in the military system
LS1124 (New grease)	• Multifak off-set grease • Compatible with MFK • Synthetic grease • Medium temperature grease (-40 to 170C) • Lubrication performance is better than MFK • Passed 1000 hr grease life test • Not available in the military system
LS1124B (New grease)	• Multifak off-set grease • Compatible with MFK • Mineral based grease • Medium temperature grease (-40 to 170C) • Lubrication performance is better than MFK • Passed 1000 hr grease life test • Not available in the military system

3.5 Evaluation of Preservative Oils

The preservative oil is used to protect the bearings from corrosion during storage. The Capella oil is currently used as preservative oil for M-G bearings. According to the technical manual, it allows the M-G bearing to be lubricated with Multifak AFB2 grease without removal of the preservative oil. For this reason, the replacement of Multifak AFB2 grease must be compatible with the Capella WF-68 oil or other candidate

preservative oils.   Due to the replacement of Multifak AFB2 grease, it is necessary to re-evaluate Capella WF-68 oil with candidate greases and to find a replacement of Capella WF-68 oil if needed. As a part of this evaluation, four military oils were selected as candidate preservative oils for the M-G bearing. These oils are currently used in precision bearing applications as a preservative oil or operational oil. All candidate preservative oils and Capella WF-68 oil were evaluated according to the test protocol which is listed in Table 9. In these tests, the Capella WF-68 oil was used as a baseline preservative oil. The test results obtained from candidate oils are shown in Table 9.

Capella WF-68 oil was originally formulated with ISO 68 mineral oil and has been used as refrigerant oil in the commercial market. This oil has been also used as preservative oil for M-G bearings and is compatible with the Multifak AFB2 grease. Its low temperature capacity is limited at -20 °C. Table 9 shows that the Capella WF-68 oil did not pass the corrosion tests (ASTM D1748, ASTM D6547) which are very important tests for the preservative oil. These corrosion tests clearly demonstrate that Capella WF-68 has very poor corrosion protection properties. Figure 3-1 shows the result of Humidity Cabinet corrosion testing. Capella WF-68 oil does not meet the military corrosion standard for the preservative oil. Therefore, Hill AFB needs a new preservative oil for M-G bearings.

MIL-PRF-32033 was formulated with ISO 10 mineral oil with additives including corrosion inhibitor and has been used in military weapon systems for a long time as a preservative oil to protect small arms and automobile parts including bearings during their storage period. This preservative oil is currently used in military applications whenever a general purpose, water-displacing, low temperature lubrication oil is required, and is widely available in the military system. Table 9 shows its physical and chemical properties obtained from the test protocol. As expected, MIL-PRF-32033 oil did not show any corrosion on the test specimens used in the ASTM D1748 Rust Protection in Humidity Cabinet tests, ASTM D6547 Bimetalic Corrosion test, and ASTM D130 Copper corrosion test. Figure 3-2 shows the result of the ASTM D1748 test. Such a lubricant can be considered as a preservative oil of the M-G bearings.

MIL-PRF-7870 is a low temperature lubricating oil and sometimes used as a preservative oil for military instrument bearing applications. It was formulated with ISO 15 mineral oil with some corrosion inhibitors and has similar physical properties to MIL-PRF-32033 preservative oil except for the corrosion protection. The corrosion test results showed that MIL-PRF-7870 did not pass the ASTM D 1748 Humidity Cabinet Corrosion, similar to Capella WF-68. The test result is shown in Figure 3-3. It indicates that MIL-PRF-7870 lubricating oil may not be enough to protect the corrosion of M-G bearings due to its weak corrosion protection property.

MIL-PRF-6085 is a synthetic based oil and has been used in aircraft instruments, electric equipment, and precision bearing applications as a lubricating oil or a preservative oil. It has excellent corrosion protection properties and good oxidation resistance characteristics. The test results confirmed that MIL-PRF-6085 did not show any corrosion spots on the test specimens used in the selected corrosion tests. Figure 3-4 shows the results of the ASTM D 1748 corrosion test. Currently, the MIL-PRF-6085 is widely available in the military lubrication system and its preservative performance has

been well accepted in military applications. The data shows that this type of oil can be used to preserve the M-G bearings.

MIL-DTL-531531 was formulated with synthetic oil (i.e., Polyalphaolefin) and has been used in the precision bearings of internal guidance gyros, accelerometers, and other instrument bearing applications. This oil is often used as a preservative oil for precision bearings. The test results show that MIL-DTL-53131 did not pass the humidity cabinet corrosion test which is shown in Figure 3-5. The data indicates this lubricant should not be considered to preserve M-G bearings.

To verify the corrosion protection property of candidate oils on the actual M-G bearings, all M-G bearings were cleaned using MIL-PRF-680 Type II solvent and dried in an oven set at 100°C over night. Once the cleaned bearings have completely dried, they are allowed to cool at room temperature. Then, all candidate oils and Capella WF-68 oil were used to lubricate the entire surface of M-G bearings. A rack was then used to let the excess oil drip off for about 2 hours. After the 2 hr drain period the bearings were placed in a 4 millimeter thick plastic bag and as much air as possible was removed from the bag. Then, the plastic bag was sealed using a heat sealer. In an alternative test specimen, wheel bearings were also included for this test. Both bearings were made with the same steel material, but the price of the wheel bearing is about $2.00, while an M-G bearing is about $1,000. For this reason, establishing some correlation of corrosion performance between M-G bearings and wheel bearings for future test was needed. For the bearing storage life test, the preserved bearings were to be maintained at laboratory room temperature (i.e., 25 °C) for more than three years. The storage test is shown in Figure 4. So far, after 3 years in storage, no corrosion has been observed on any bearings lubricated with candidate preservative oils or Capella WF-68 oil for this testing period. Even the poor corrosion protection oils showed no sign of corrosion on either the M-G bearings or the wheel bearings. It appears that the packing material and procedure is a key element to prevent corrosion on bearings. In this case, the M-G bearing packing procedure significantly helps in preventing corrosion of M-G bearings. However, we found that all plastic bags leaked after a 2 year storage period. It appears that new types of plastic bags are needed for long term bearing storage.

To determine the compatibility between grease and preservative oil, candidate greases were tested with two military preservative oils (i.e., MIL-PRF-32033, MIL-PRF-6085) using a modified ASTM D1743 test method which measures the corrosion using the actual bearing. Based on the laboratory test results, these two preservative oils selected were considered as the best candidate preservative oils for M-G bearings. This modified ASTM D1743 procedure is not only to determine the compatibility of two lubricants, but also to determine the corrosion protection capability by the mixture of oil and grease. For the baseline test, Capella WF-68 oil and Multifak AFB2 grease were tested according to the modified ASTM D1734 test method. The baseline test results reveal that this combination provided very poor corrosion protection capability even though they are chemically compatible. This test result is shown in Figure 5. Unlike this combination, all other candidate greases did not have any compatibility/corrosion problem with either MIL-PRF-6085 or MIL-PRF-32033 oil. The compatibility/corrosion test results are

summarized in Table 10 and Figure 6 demonstrates the corrosion test result obtained from GAAH and MIL-PRF-6085 oil.

Table 9. The Test results of candidate preservative oils for M-G bearings

TEST	CAPELLA WF-68 (FL-13606-10)	MIL-PRF-32033 (FL-12742-08)	MIL-PRF-6085 (FL-13609-10)	MIL-PRF-7870 (FL-13610-10)	MIL-DTL-53131 (FL-12617-07)
ASTM D445 @40C (Viscosity, cSt) @100C @-20C @-30C @ -40°C @ -54°C	63.61 6.58 28992.71 Almost no flow No flow No flow	11.16 2.85 ND ND 3460.87 41013.44	13.21 3.49 ND ND 1703.99 10321.41	17.65 3.98 ND ND 2514.77 14072.78	61.78 10.08 2705.68 7403.28 24469.84 No flow
ASTM D97 (Pour Point)	-36°C	-66°C	-78°C	-66°C	-51°C
ASTM D6304, Proc. C (Water Content)	40.7 ppm, 0.0041%	193.1 ppm, 0.0193%	471.9 ppm, 0.0472%	62.7 ppm, 0.0063%	46.7 ppm, 0.0047%
ASTM D91, ml (Precipitation Number)	>0.05	>0.05	>0.05	>0.05	>0.05
ASTM E1131, 100 °C, TGA, % (Evaporation Loss)	3.97	24.87	0.319	0.208	0.023
ASTM D974 (Acid and Base Number)	0.0056	0.1542	0.1360	0.1346	0.0042
ASTM D1748 (Rust Protection in Humidity Cabinet)	F, F, F / Fail	P, P, P / Pass	P, P, P / Pass	F, F, P / Fail	F, F, F / Fail
ASTM D130 (Copper Corrosion)	1a, 1a	1a, 1a	1a, 1a	1b, 1b	1a, 1a
ASTM D6547 (Bimetallic Corrosion)	P, F, F / Fail	F, P, P / Pass	P, P, P / Pass	P, P, P / Pass	P, P, P / Pass
FTM 791.3458 @ -45°C, 72 h (Low Temperature Stability)	Unstable/No flow	Stable	Stable	Stable	Stable
ASTM D6186, 180°C, min (Oxidation, PDSC)	2.98	9.27	83.21	25.5	24.9
ASTM D4172, Scar dia, mm (Four Ball Wear)	0.714	0.751	1.098	0.556	0.67
ASTM D92 (Flash and Fire Points), °C	201.3/220.3	144.3/151.3	244.3/264.3	236.3/262.3	272.3/298.3
Storage Stability using M-G bearings @25C, 1 yr	No corrosion	No corrosion	No corrosion	No corrosion	No corrosion
Compatibility between oils & greases	Pass	Pass	Pass	Pass	Pass

Table 10. Compatibility/Corrosion Test Results between Candidate Preservative Oils and Greases

Grease	Capella WF-68	MIL-PRF-6085	MIL-PRF-32033
MFK	F,F,F/Fail	NT	NT
GAA	NT*	P,P,P/Pass	P,P,P/Pass
Nye	NT	P,P,P/Pass	P,P,P/Pass

Castrol	NT	P,P,P/Pass	P,P,P/Pass
Shell	NT	P,P,P/Pass	P,P,P/Pass
GIA	NT	P,P,P/Pass	P,P,P/Pass
LS-1124	NT	P,P,P/Pass	P,P,P/Pass
LS-1124B	NT	P,P,P/Pass	P,P,P/Pass

* Not tested

4. RECOMMENDATIONS FOR PNS TEST

On the basis of the laboratory evaluation, TARDEC recommend the following greases and oils for the PNS grease qualification test which was planned in Part II of the Hill AFB Grease replacement Program. This recommendation was made based on the lubrication performance, compatibility and availability. The recommended lubricants are listed in the following Table 11.

Table 11. Recommendations for PNS Test

Order of Recommendation	Grease	Preservative Oil
First	MIL-PRF-10924H	MIL-PRF-6085
Second	MIL-PRF-32014	MIL-PRF-32033
Third	Shell Alvania RL-2, LS1124, LS1124B	-
Not recommended	MIL-PRF-81322, MIL-PRF-10924G, MIL-PRF-23827	Capella WF-68, MIL-PRF-7870, MIL-DTL-53131

Figure 1. ASTM D3527 Grease Life Test Apparatus

Figure 2. Elastomer compatibility test results with GIA and other candidate greases

Figure 3. Corrosion Test Results obtained from ASTM D 1748 Test Method

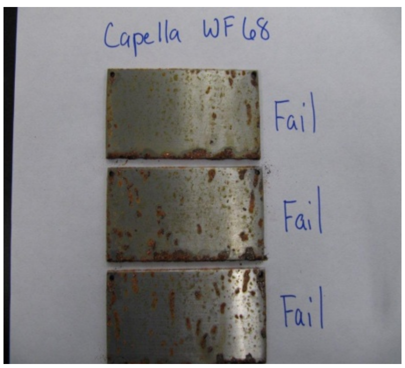


Figure 3-1. Capella WF-68

Figure 3-2. MIL-PRF-32033

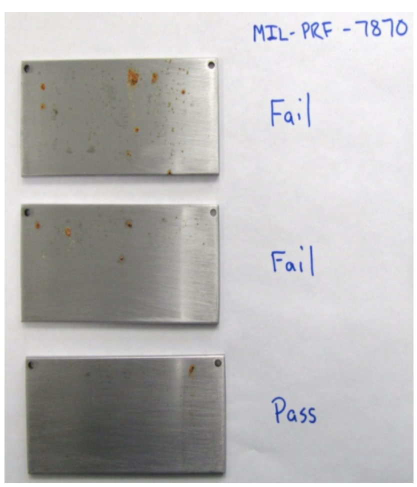


Figure3-3. MIL-PRF-7870

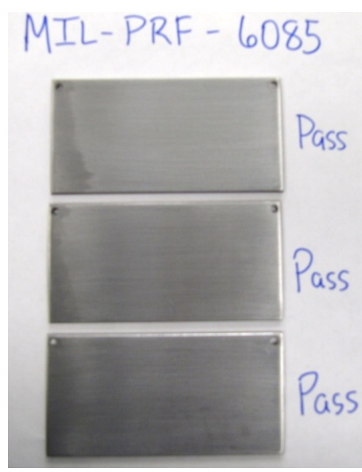


Figure 3-4. MIL-PRF-6085

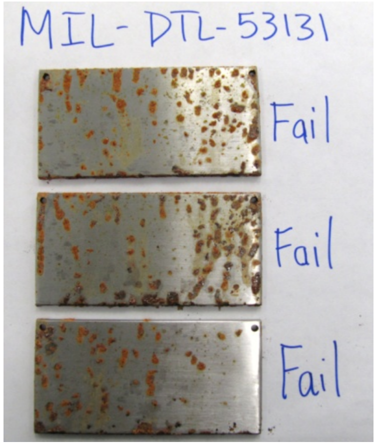


Figure 3-5. MIL-DTL-53131

Figure 4. Storage Stability Test of Candidate Preservative Oils in M-G Bearings

Figure 5. Corrosion/Compatibility Test with Capella WF-68 and MFK

Figure 6. Corrosion/Compatibility Test with MIL-PRF-6085 and GAAH

5. PNS 1000 HRS M-G GREASE TEST

5.1 TEST PLAN

The M-G grease qualification test plan was developed by Harris Consulting International Company as a part of the M-G bearing grease replacement program (Ref 1). This field test was originally planned to certify the candidate M-G grease which can replace Multifak AFB2 grease. The MIL-PRF-10924H grease was recommended for the PNS M-G test and was approved at the 2011 Mid-term review meeting held at Hill AFB. MIL-PRF-6085 oil was also approved for the M-G test as a preservative oil. For the test, two M-G units (M-G SN 419, M-G SN 860) were utilized. One unit was used for evaluating the candidate grease and the second unit was used for the mixture with Multifak AFB2 grease (see Figure 7). The M-G tests were conducted for 1000 hours at the Portsmouth Naval Shipyard. The acceptance criteria used in this test were the operational conditions (high temperature, vibration, torque level, etc.), visual inspection of grease and bearings after test, and the grease analysis and bearing inspection after the test. The test bearing inspection was done by TIMKEN Bearing Inspection (TBI) Company before and after the 1000 hr M-G test.

5.1.1 GREASE MIXING PROCEDURE

To verify the compatibility between MIL-PRF-10924H grease and Multifak AFB2 grease, the test grease was mixed approximately 50:50. The grease cavities and tubes leading to the bearings have a capacity of approximately 5cc for grease and cavities and tubes are empty at start up. In order to obtain approximately a 50:50 mixture 30cc of grease was added using a new clean grease gun. At the initial startup of the M-G, air and the solid base of the grease was expelled from the inter bearing causing a minimal amount of noise. Then, the grease was slowly and uniformly mixed by the mechanical mixing procedure. This procedure was developed by Hill AFB to simulate the grease re-lubrication procedure used in the M-G units.

5.1.2 GREASE EVALUATION CRITERIA

The following acceptance criteria were developed based on the field performances and have been used for the M-G grease qualification test:

a) Mechanical binding or degradation that clearly results in a bearing and grease failure, or excessive noise/rumbling.
b) Degradation of performance beyond pretest record or equipment specification requirements:
    i) AC input current >20 amps,
    ii) DC input current > 160 Amps,
    iii) Surface temperature > 180º adjusted to 72º ambient, or
    iv) Vibration >1 mil.

c) Grease consistency (50% change).
d) Oxidation test (80% change).

e) Evaporation test (50% change).
f) Dropping point test (50% change).
g) Grease wear test by SRV
h) Degradation of additives and wear particle contamination by X –ray.
i) Grease life prediction in M-G system.
j) Bearing damages by the post bearing inspection.

5.2. PNS TEST RESULTS

A summary of the M-G tests identified by their designated codes is presented in Table 12. The M-G S/N 419 unit was used for determining the compatibility of MIL-PRF-10924H and Multifak AFB2 grease, while the candidate grease (MIL-PRF-10924H) was tested in the M-G S/N 860 unit (Ref. 2). During the test, all data (including test temperatures and torque level) was recorded, and no operational problems were observed. After the completion of the M-G 1000 hr test, the bearings and greases were visually inspected by TARDEC. The candidate grease did not show any abnormal behavior and performed well in the M-G bearings. In addition, no compatibility problem was observed in the M-G S/N 419 test unit evaluating the mixture of greases. The mixture also provided very good lubrication performance in the M-G bearings (Ref. 3). The tests validated the O-ring used in the M-G units was clearly compatible with both greases. This elastomer compatibility result is shown in Figure 8. Two additional M-G bearing photos, which display the excellent conditions of the grease and bearings, are shown in Figures 9-10.

Table 12. PNS M-G Test Units and Tested Grease Condition

	M-G S/N 419	M-G S/N 860
Test Grease	50:50 Mixture of MIL-PRF-10924H and Multifak AFB2 grease	MIL-PRF-10924H
Duration	1000 hours without off-cycle	1000 hours without off-cycle
Test Bearings	3	3
Operational Temperatures	77-117 °F	80-114 °F
Vibration or Noise Level	Very Low	Very Low
Grease condition	Excellent	Excellent

5.2.1. GREASE ANALYSIS

To inspect the used greases, about 6 grams samples were collected from each M-G bearing for the laboratory analysis. All six samples were analyzed according to the test protocol. This protocol consists of dropping point test, evaporation, oxidation, wear, friction coefficient, grease consistency, additive analysis by X-ray, and predicted grease life. The grease samples collected were identified by their designate codes from S-1 to S-3 for samples collected from the M-G S/N 419 unit, and S-4 to S-6 for samples collected from the M-G S/N 860 unit. Table 13-15 lists the test protocol and summarizes the

results of grease analysis. Overall the physical properties of the used greases didn't substantially change with exception of mixed grease oxidation stability during 1000 hr operation. Due to the limited size of the grease sample, the consistency of grease was measured by a finger technique. There was no change in the consistency of grease after the 1000 hr M-G test. The oxidation stability was determined using the Pressure Differential Scanning Calorimetry (PDSC) at 180 °C. The 50:50 mixture grease has been oxidized about 12 % during the 1000 hr operation, while MIL-PRF-10924H grease was slightly oxidized. This change does not affect the grease service life and other properties were not significantly changed during the PNS test. The overall grease conditions were very good for the 1000 hrs of M-G operation.

Table 13. Grease Analysis of M-G 1000 hr Tests

Property	Test Method	M-G S/N 419				Analysis Results	M-G S/N 860				Analysis Results
		50:50 Mixture*	S-1	S-2	S-3		MIL-PRF-10924H	S-4	S-5	S-6	
Dropping point	ASTM D2265, C	210	221	204.3	272.3	Slight change	307.3	283	279.3	255.5	Slight change
Evaporation, 100 C, 1 h, %	ASTM E1131	0.46-0.71	1.42	0.54	2.1	Slight change	0.71	0.57	0.90	1.81	Slight change
Oxidation, 180C, min	ASTM D5483	29.2	8.2	10.0	22.7	About 12 % oxidized	31.8	28.4	18.3	27.8	Slight oxidized
Wear Test @80C	SRV	0.73-0.81	0.86	0.66	0.67	No change	0.73	0.76	0.89	0.88	No change
Friction coefficient @80C	SRV	0.12	0.15	0.13	0.13	No change	0.12	0.13	0.12	0.13	No change
Grease consistency	ASTM D 217	No. 2	No.2	No. 2	No. 2	No change	No.2	No.2	No.2	No.2	No change

* 50:50 % Mixture of MIL-PRF-10924H and Multifak AFB2 grease

The lubricating grease is a consumable material and its physical and chemical properties are normally degraded by the bearing shear action and high operational temperatures. Grease service life is significantly affected by depletion of additives and contamination. An X-ray technique is used to evaluate service life changes. Table 14 lists nine chemical elements detected by this technique. To make a comparison between new and used grease, fresh samples of both greases (MIL-PRF-10924H, Multifak AFB2) were analyzed. If a chemical element was not found in the fresh samples, it can be considered as a contamination which came from the bearing materials or other. The results indicate the used grease formulations did not significantly degrade. However, the analysis noted about 50 % of the sulfur compound was depleted in the grease samples collected from M-G S/N 860 unit which was tested with MIL-PRF-10924H (GAA) grease. In a subsequent investigation, its QPL record indicated a high level of sulfur compound EP additive. It appears that the loss of sulfur compound may be an excessive amount of additive in the grease formulation. This does not affect the grease performance in the bearing operation. The X-ray also detected trace amounts of contamination in both used greases. These trace amounts can be ignored for the bearing operation.

Table 14. Additive Depletion and Contamination Analysis by X-ray Technique

Element	New Grease		M-G S/N 419(Mixture)			Analysis Results	M-G S/N 860(GAA)			Analysis Results
	MIL-PRF-10924H, %	Multifak AFB2, %	S-1	S-2	S-3		S-4	S-5	S-6	
Si	0.839	0.072	0.425	0.395	0.477	Slight change	0.473	0.468	0.402	Slight change
P	N	N	0.005	0.005	N	Contamination	N	0.004	0.004	Slight change
S	0.848	0.093	0.328	0.391	0.534	Slight change	0.497	0.434	0.394	50 % depletion
Ca	0.045	N	0.023	0.021	0.028	No change	0.026	0.025	0.021	No change
Cr	N	N	0.052	0.002	0.001	Contamination	0.001	0.001	0.001	Contamination
Mn	N	N	0.006	N	N	No change	N	N	N	No change
Fe	0.004	N	0.458	0.155	0.054	Wear	0.054	0.038	0.029	Wear
Ni	N	N	0.019	N	N	No change	N	N	N	No change
Cu	N	N	0.051	0.027	0.003	Wear	0.006	0.014	0.022	Wear
Zn	0.108	N	0.041	0.049	0.064	Slight change	0.062	0.057	0.046	Decrease
Sn	N	N	0.112	0.097	N	Contamination	N	0.053	0.131	Contamination
Ba	N	N	N	N	N	No change	0.008	0.007	0.007	Contamination
W	0.295	N	0.098	0.113	0.157	Slight change	0.138	0.131	0.098	Slightly change
Re	0.006	N	0.002	0.002	0.002	No change	0.002	0.002	0.001	No change

The bearings in the M-G units are injected with about 10cc of new grease every year. Any candidate grease has to at least last one year of continuous operation. Due to the unavailability of M-G units, the field test (actual M-G test) was conducted for only 1000 hrs which is about 42 days of operation. Therefore, the candidate grease life was predicted using a decomposition kinetic model at actual operational temperature (i.e., 43 °C). The results are shown in Table 15. MIL-PRF-10924H was projected to have about 2.3 years of service life in the M-G system, while its mixture with Multifak AFB2 grease was predicted at 2.5 years in the M-G system. It is assumed that Multifak AFB2 grease tended to influence the service life of the mixture. This result is very similar to that obtained from the laboratory dynamic test. It also appears that MIL-PRF-10924H grease does not have any problem meeting the relubrication interval of M-G bearings. Currently, MIL-PRF-10924H grease lubricates vehicle wheel bearings for more than one year.

Table 15. Prediction of Grease Life in M-G Systems by Decomposition Kinetic Model

Sample	Induction time before 1000 hr test, @180°C, min	Induction time after 1000 hr test, @180°C, min	Decomposition Kinetic Life @ 43 °C, hrs	% Grease oxidized for 1000 hr test	Predicted grease life in M-G unit @ 43 °C, yrs
M-G S/N 419, 50:50 mixture*	17.2	13.6	16715	2.5	2.5
M-G S/N 860, MIL-PRF-10924H	31.8	24.8	16,896	2.7	2.3

* 50:50 mixture of MIL-PRF-10924H and Multifak AFB2 grease

5.2.2. BEARING INSPECTION

The tested M-G bearings were inspected by TIMKEN Bearing Inspection (TBI) Company. TBI reported that no wear or corrosion problems were detected in the tested bearings, and the bearing conditions were excellent compared to the new bearings which were pre-inspected prior to the 1000 hr M-G test (Ref.4). During the inspection period, TBI also found brownish stains (corrosion) on the surfaces of bearings tested in the M-G S/N 860 test unit (Figure 11). This unit has been tested with only MIL-PRF-10924H grease. In the follow up investigation, TBI determined that the most likely cause of stains on the bearings was a result of exposure to cleaning solution (aqueous cleaner) and the bearing was not rinsed properly after cleaning (Ref.5). These aqueous cleaners have been used for the M-G bearing cleaning applications before/after the test at both TBI and PNS. In this finding, there was no evidence to support the tested grease was the source of the stain. This finding was also confirmed by TARDEC investigation (Ref.6). Stains on bearings are normally created by several sources (heat, corrosion, or grease, etc.). Stains created by heat and corrosion are irreversible causing permanent damage to the bearing. If the stain is a result of the depletion of excessive Extreme Pressure (EP) additive, having Sulfur Compound, it does not affect the bearing operation at all and is a common condition. However, there was no additional data to support the finding from this stain investigation. Due to the inconclusive results, TARDEC recommended an additional PNS M-G test to resolve the stain issue, and the recommendation was approved at the 2012 Annual review meeting which was held at Hill AFB (Ref 7 and 8).

6.0. VERIFICATION TEST

To verify the results of the 2012 PNS M-G test and to resolve the M-G bearing stain issue, a verification test was initiated using a M-G unit (S/N M-G 860) and MIL-PRF-10924H grease at PNS. The verification test plan (Ref 9) was also developed, by Harris Consulting Company, based on the modification of the original grease qualification test plan (Ref 1). All M-G test conditions and procedures were same as before, but the bearing cleaning procedure was altered as explained below. No mixture of grease was tested in this verification test. The post M-G bearing analyses were a visual inspection and bearing surface roughness (RA) inspection using an Optical Surface Profilometer. The acceptance criteria of this bearing surface analysis was also developed in comparison of RA value with that of the previous tested M-G bearing (2012) which was inspected by TIMKEN Tribology Center. As a part of the stain investigation, the cleaning solvent used was changed from Isopropyl alcohol (IPA) to MIL-PRF-680 Type II solvent for this verification test. The solvent replacement was discussed at the 2012 Annual review meeting and as a follow-up action, a comparison study was conducted between IPA and MIL-PRF-680 Type II solvent for M-G bearing cleaning applications. The study results indicated that IPA did not create the stain problem on the M-G bearing surface. However, based on the comparison study, TARDEC has recommended to replace IPA with MIL-PRF-680 Type II solvent due to the high flammability and weak cleaning power (Ref 10) of IPA.

6.1. VERIFICATION TEST RESULTS

A summary of the 2013 M-G test results is presented in Table 16. During the test, all data including test temperatures and torque level were recorded, and no operational problems were observed (Ref 11). After the completion of the M-G 1000 hr test, the bearings and greases were visually inspected by the Grease team members including TARDEC. The candidate grease did not show any abnormal behavior and performed well in the M-G bearings. Figure 12 shows the candidate grease conditions on both sides of a M-G bearing after 1000 hrs of operation. No stain was observed on bearing races or rollers in all three bearings. But slight discoloration was observed on the brass roller retainer in certain small areas. Figure 13 shows both M-G bearings having stains (2012 test) and without stains (2013 test). There was no evidence of corrosion or wear on the bearing surface which is shown in Figure 14. As expected, the O-ring used for a grease seal material was compatible with MIL-PRF-10924H grease. The photo shown in Figure 15 demonstrates the results of seal compatibility showing a new and used O-ring. The overall inspection results indicated that the 2013 M-G test had almost identical results compared with those of the 2012 M-G test, excluding the bearing stain issue observed in the 2012 M-G test.

Table 16. Visual Inspection of M-G Bearings & Grease after 2013 M-G Test

	M-G S/N 860
Test Grease	MIL-PRF-10924H
Duration	1000 hours without off-cycle
Test Bearings	3
Operational Temperatures	83.2-119.6 °F
Vibration or Noise Level	Very Low
Grease condition	Excellent and sufficient amount of grease remains in the bearings
Stains on Bearings	No stains on bearing races or roller. Slight discoloration noted on the brass roller retainer in certain small areas.
Corrosion problem	No evidence of corrosion observed
O-ring problem	No deficient condition observed on O-rings
Wear and Fatigue problem on M-G bearings	No severe wear or evidence of fatigue observed

6.2. GREASE ANALYSIS FOR VERIFICATION TEST

For the laboratory analysis, about 4 grams of grease sample was collected from each M-G bearing identified by the bearing location. All three samples were analyzed according to the test protocol used in the 2012 M-G test. This protocol consisted of dropping point test, evaporation, oxidation, wear, friction coefficient, grease consistency, additive analysis by X-ray, and predicted grease life. The grease samples collected were identified by their designate codes from S-7 to S-9. Table 17-19 lists the test protocol

and summarizes the results of grease analysis. The physical properties of the used grease did not change significantly during the 1000 hrs of operation. Due to the limited size of grease samples, the consistency of grease was not measured. But, in visual inspection, the consistency of the grease changed only slightly after the test. The oxidation stability was slightly changed due to the 1000 hrs of operation. It is considered to be normal degradation and does not affect the service life of M-G bearings. The other properties of the greases were not significantly changed during the PNS test. The overall grease condition was very good for the 1000 hrs of M-G operation.

Table 17. Grease Analysis of 2013 M-G 1000 hr Tests

Test Method		M-G S/N 860				Analysis Results
		MIL-PRF-10924H	S-7 (AC bearing)	S-8 (Center bearing)	S-9 (DC bearing)	
Dropping point	ASTM D2265, C	>300	>300	309.0	311.0	No change
Evaporation, 100 C, 1 h, %	ASTM E1131	0.8	0.54	0.48	0.43	Slight change
Oxidation, 180C, min	ASTM D5483	61.6	35.2	33.0	28.9	Slight oxidized
Wear Test @80C	SRV	0.61	0.62	0.58	0.61	No change
Friction coefficient @80C	SRV	0.1	0.09	0.09	0.1	No change
Grease consistency	ASTM D 217	No.2	No.2	No.2	No.2	No change

To inspect the depletion of additives and contamination level of the used grease, the M-G greases collected were analyzed by X-ray technique. Table 18 lists eleven chemical elements detected by the X-ray technique. Samples of fresh and used (post-test) grease were analyzed. If the chemical element was not found in the fresh greases, it can be considered as a contamination or wear particles which came from the bearing materials or outside the system. The results indicated that the used grease did not significantly degrade. The X-ray also detected trace amounts of wear particles (copper, zinc, tin, barium) in the used greases. It appears that these wear particles came from the M-G bearing retainer which is made with brass and bronze materials. These trace amounts can be ignored for the normal bearing operation.

Table 18. Additive Depletion and Contamination Analysis
by X-ray Technique (2013 M-G Test)

Element	MIL-PRF-10924H (%)	M-G S/N 860			Analysis Results
		S-7 (AC bearing)	S-8 (Center bearing)	S-9 (DC bearing)	
Si	0.0	0.0	0.0	0.0	No change
P	0.086	0.0	0.0	0.107	Slightly change
S	1.245	0.076	0.615	1.190	Slightly change
Ca	0.196	0.092	0.109	0.132	Slightly change
Cr	0.0	0.001	0.0	0.0	No change
Mo	4.449	4.077	2.669	3.141	9-40 % depletion
Fe	0.0	0.085	0.111	0.205	Wear
Cu	0.0	0.164	0.202	0.711	wear
Zn	0.0	1.873	1.632	2.868	wear

Sn	0.0	0.109	0.077	0.0	Contamination
Ba	0.0	0.12	0.13	0.14	Contamination

To recheck the candidate grease life in the M-G bearing system, the MIL-PRF-10924H grease life was predicted based on 1000 hrs of performance in the M-G system, using a decomposition kinetic model at actual operational temperature (i.e., 43 °C). The results are shown in Table 19. The service life of MIL-PRF-10924H grease is predicted to be about 1.74 years in M-G system and it was very similar to that of the 2012 prediction (2.3 years reported in Table 15). This prediction life exceeds the current one year republication interval for the M-G bearing system. It appears that MIL-PRF-10924H grease meets the relubrication interval of the M-G bearings. In addition, the predicted life (2.5 years reported in Table 15) of the mixed grease (GAA and Multifak AFB2) also meets the current relubrication interval.

Based on the grease analysis, the used grease was in excellent condition with no severe degradation detected after the 1000 hrs of operation.

Table 19. Prediction of Grease Life in M-G Systems by Decomposition Kinetic Model

Sample	Induction time before 1000 hr test, @180°C, min	Induction time after 1000 hr test, @180°C, min	Decomposition Kinetic Life @ 43 °C, hrs	% Grease oxidized for 1000 hr test	Predicted grease life in M-G unit @ 43 °C, yrs
M-G S/N 860, MIL-PRF-10924H	46.4	22.0	12,227	4.2	1.74

6.3. BEARING INSPECTION FOR VERIFICATION TEST

All M-G bearings tested were visually inspected at PNS using 10X microscopy. There was no severe wear, no stains on rollers or races, no corrosion and no fatigue on the tested bearings, except for slight discoloration on a small area of the roller brass retainer. For further bearing inspection, a surface roughness analysis (RA) was performed using an Optical Surface Profilometer which is shown in Figure 16. This optical instrumentation was used to measure a bearing surface’s profile in order to quantify its roughness (i.e., wear or fatigue). For the bearing analysis, a reference M-G bearing was used to make the surface roughness comparisons. This reference bearing was used in the previous M-G bearing test and inspected by TIMKEN Tribology Center. Table 20 shows the results of the bearing surface roughness analysis. The results show that RA values of the tested bearings range from 55.8 nm to 97.5 nm. It indicates that the tested M-G bearings still have very smooth surfaces and there was no evidence of bearing damage. In addition, there were no significant differences in RA values between M-G bearings and the reference bearing. No wear or corrosion problems were detected in the tested bearings, and the bearing conditions were excellent as compared to the reference bearing. Figures 17 & 18 show a three dimensional Interactive Display of a 2013 tested bearing and the reference bearing (2012 Tested M-G Bearing).

Table 20. M-G Bearing Surface Roughness Analysis by Optical Surface Profilometer

	Bearing from* 2012 PNS test	AC bearing	Center bearing	DC bearing
Bearing Surface Roughness (RA), nm	55.8-75.2	81.5-88.7	63.6-84.2	58.5-97.5

* M-G bearing which was inspected by TBI in 2012 PNS test.

During the inspection period, it was found that the brass bearing retainers showed slight discoloration on small areas (see Figure 14). The brass metal is a copper alloy with zinc metal and generally, with time, creates an oxidized metal film (dark brown color) on the surface of brass metal to prevent further oxidation. Generally, the discoloration on the brass metal is created by several sources (heat, corrosion, or grease, etc.). To investigate the potential cause of the brass discoloration in the M-G tests, a copper corrosion test was re-conducted to verify the copper corrosion protection property of the MIL-PRF-10924H grease. The test results showed that it met the specification requirement. The data suggested the grease is compatible with brass material and there was no chemical reaction between the grease and the bearing brass metal. In this case, the possible cause of discoloration could be localized high heat on the bearing surface. Unfortunately, the localized heat cannot be well detected by a temperature sensor because a heat spike does not last long enough to be detected. This localized high heat in the bearing is normally generated by the overfilling of grease which can reduce the bearing cooling effect. The significant amount of excess grease is detected in Figure 12 (back side of AC M-G bearing). Generally, the slight discoloration on the bearing brass retainer does not affect the bearing operation at all. This type of discoloration is often found in high speed bearing operation due to the heat imbalance.

7. SUMMARY

As a part of the Hill AFB grease replacement program, TARDEC performed the laboratory evaluation and participated in the M-G 1000 hr grease qualification test to develop/find a new M-G grease and preservative oil for the Minuteman III Missile system. The results of this study are summarized in the following accomplishments:

1. Laboratory grease testing program has been developed using eight candidate greases and four preservative oils. For the baseline study, Multifak AFB2 grease and Capella WF-68 oil were also fully evaluated in order to compare with candidate greases and preservative oils.

2. The grease compatibility test was performed according to the ASTM D6185 test method with Multifak AFB2 grease. The test results showed that all candidate greases except for MIL-PRF-81322 grease were chemically compatible with Multifak AFB2 grease.

3. The test results showed that Multifak AFB2 grease has poor corrosion protection and oxidation stability. All candidate greases were equal or better than those of Multifak AFB2 grease. Among them, MIL-PRF-10924H grease was the best in overall performance, while GIA showed very poor elastomer compatibility with the actual O-ring used in the M-G bearing system.

4. To verify the high temperature performances of candidate greases, the dynamic laboratory test was developed to simulate the M-G test and performed at the operation conditions of M-G bearings (i.e., 83 C, 1800 rpm). All candidate greases were passed without any major issues for 1000 hours.

5. The test results showed that Capella WF-68 oil has very poor corrosion protection and does not meet the corrosion protection requirement under the tested conditions. MIL-PRF-6085 and MIL-PRF-32033 preservative oils are excellent for corrosion protection. These oils are currently used in military bearing applications as preservative oils.

6. Based on the laboratory evaluation and market study, TARDEC recommended MIL-PRF-10924H grease and MIL-PRF-6085 oil for the PNS 1000 hr M-G test.

7. To certify MIL-PRF-10924H grease as a replacement of Multifak AFB2 grease, the field test was conducted using two M-G units at PNS for 1000 hours. One M-G unit was tested with a 50:50 mixture of MIL-PRF-10924H and Multifak AFB2 greases, while the other unit was tested with only MIL-PRF-10924H grease. The test results indicated that the greases did not have any abnormal behavior during the 1000 hour operation, no incompatibility issues were observed, and the resultant grease conditions were excellent.

8. The tested M-G bearings were inspected by TIMKEN Inspection Company. No wear or corrosion was detected on the bearing surface and no dimensional changes were noted. During inspection a stain or discoloration of the bearing surface was. This stain was later identified as corrosion initiated by aqueous solvents used in the cleaning process. Aqueous solvents are not acceptable for the bearing cleaning application.

9. To determine the relubrication interval of MIL-PRF-10924H and its mixture in the M-G system, the grease service life was predicted using a decomposition kinetic model. It was found that the service life of MIL-PRF-10924H grease was predicted in the range of 1.74 years to 2.3 years in the M-G system, while its mixture was projected at about 2.5 years. It appears that the predicted MIL-PRF-10924H grease life meets the yearly relubrication interval of M-G bearings.

10. All data obtained from the grease qualification test which was conducted in 2012 has been confirmed by the 2013 verification test. The MIL-PRF-10924H grease did not show any abnormal behavior and performed well in the 2013 M-G test. No stain was observed in the 2013 test bearings, except for slight discoloration on the brass retainer in certain small areas which is of no consequence. In addition, no corrosion or severe wear was observed. The tested candidate grease was in excellent condition after the 1000 hr verification test.

8. RECOMMENDATIONS

On the basis of the results of laboratory evaluation, the PNS 1000 hr M-G test and the follow-on 1000 hr verification test, TARDEC recommends the following grease, preservative oil and cleaning solvent, listed in Table 21, as replacements of the current M-G lubricants and cleaning solvent. MIL-PRF-10924H is a major lubricating grease for military ground vehicles and equipment, and will be continuously available in military supply systems.

Table 21. Recommendations for M-G Bearing Lubricants and Cleaning Solvent

	Current M-G lubricant and Cleaning Solvent	Replacement Lubricant and Cleaning Solvent
Grease	Multifak AFB2	MIL-PRF-10924H
Preservative Oil	Capella WF-68	MIL-PRF-6085
Cleaning Solvent	Isopropyl Alcohol (IPA)	MIL-PRF-680 Type II

REFERENCES

1. Qualification Test/Procedure for Minuteman III Motor-Generator (M-G) Bearing Grease Replacement, Harris Consulting International Co., May 16, 2011.
2. Minutes of Meeting, PNS, March 12, 2012.
3. Minutes of Meeting, PNS, May 1, 2012.
4. Bearing Condition Analysis No. 723782, TIMKEN Inspection Inc, June 29, 2012.
5. TIMKEN Stained Bearing Investigation, August 30, 2012.
6. Briefing Charts on Annual Progress Review for Hill AFB Grease Replacement Program, September 19, 2012.
7. Minutes of Meeting, Hill AFB, September 19, 2012.
8. TARDEC Technical Report (Interim) No. TR-23270 on Minuteman III Motor-Generator Bearing Grease Replacement, July, 2012.
9. Test plan/Procedure for Bearing Grease Replacement, Harris Consulting Co., March, 2013.
10. TARDEC Information Paper on Evaluation of Isopropyl Alcohol 9IPA) compared with MIL-PRF Type II solvent, February 19, 2013.
11. Minutes of Meeting, PNS, May 6, 2013.

Figure 7. PNS 1000 hr M-G Test

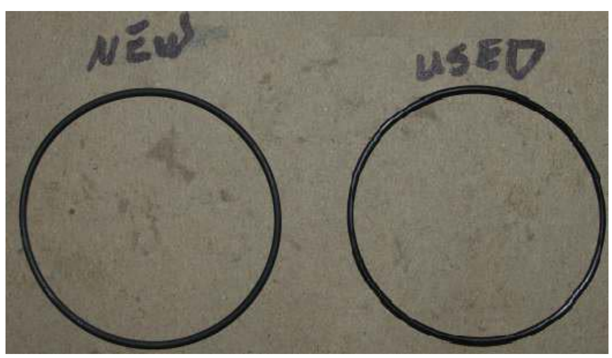
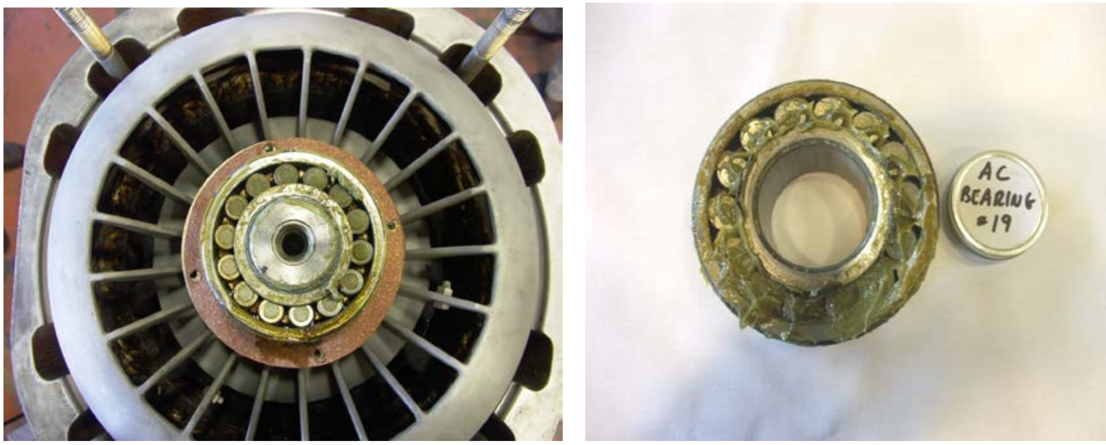


Figure 8. Elastomer Compatibility Results obtained from PNS Test

Figure 9. Inspection on 50:50 Mixture Grease after PNS Test

Figure10. Inspection on MIL-PRF-10924H after PNS test

Figure 11. M-G Bearing with stain after cleaning by TBI



(a) Front side of AC M-G bearing (b) Back side of AC M-G bearing

Figure 12. M-G Bearing located at AC System

Figure 13. Comparison between two PNS test results on the surface of M-G Bearings (Stain and no stain)

Figure 14. No corrosion or severe wear on bearing roller

Figure 15. Seal Compatibility Results obtained from 2013 PNS Test

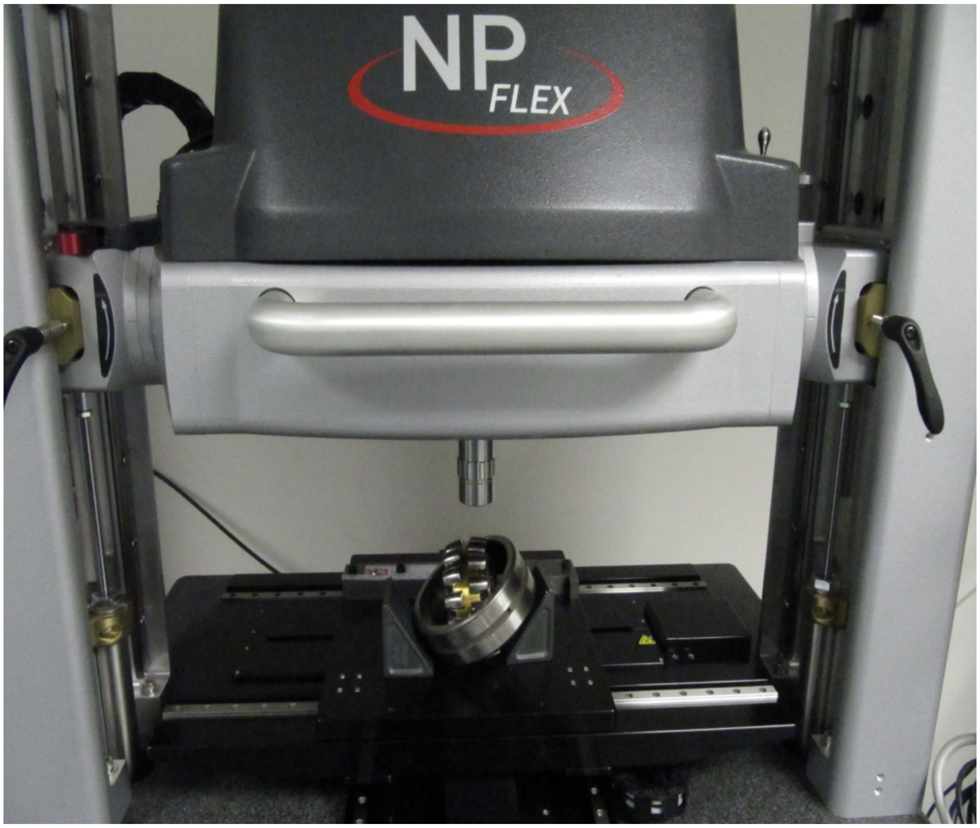


Figure 16. Optical Surface Profilometer

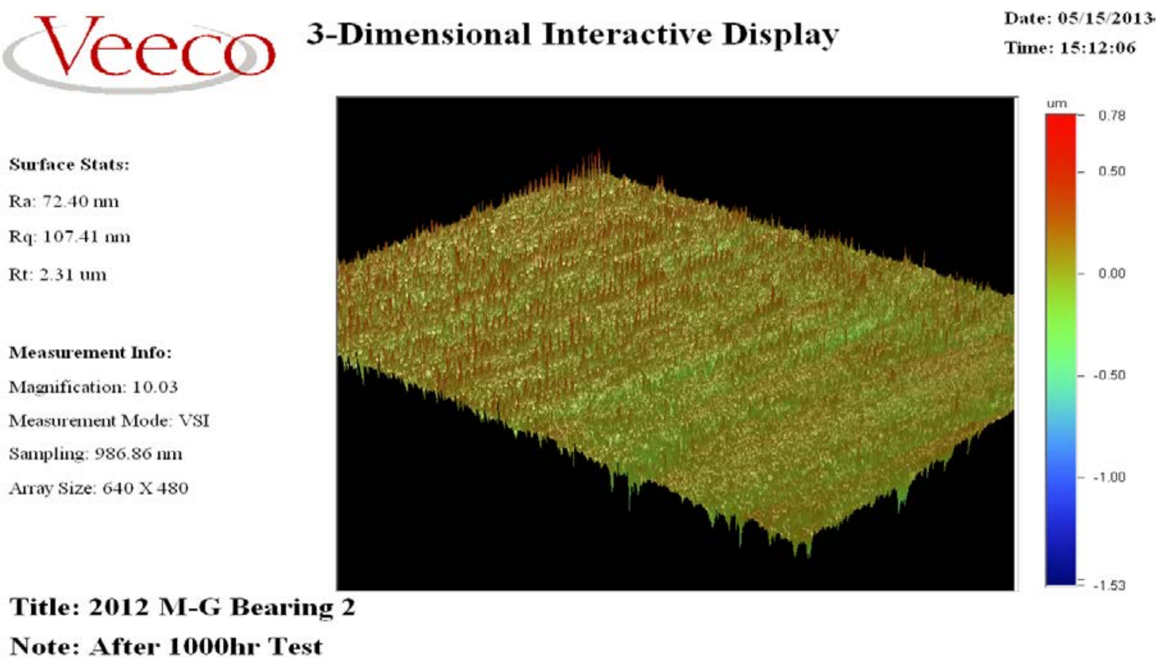


Figure 17. Roughness of M-G Bearing after 2012 PNS Test

Veeco **3-Dimensional Interactive Display**

Date: 05/15/2013
Time: 15:47:52

Surface Stats:

Ra: 84.15 nm

Rq: 116.81 nm

Rt: 2.48 um

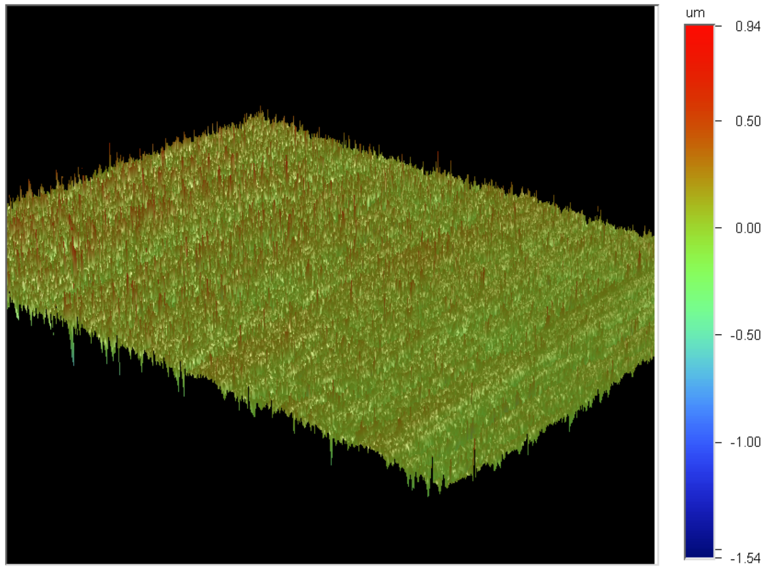
Measurement Info:

Magnification: 10.03

Measurement Mode: VSI

Sampling: 986.86 nm

Array Size: 640 X 480



Title: 2013 C Bearing #16

Note: After 1000hr M-G Test 2

Figure 18. Roughness of M-G Bearing after 2013 PNS Test